

# Detection of the 2175 Å dust feature in Mg II absorption systems

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## ABSTRACT

The broad absorption bump at 2175 Å due to dust, which is ubiquitous in the Galaxy and is seen in the Magellanic clouds, is also seen in a composite spectrum of Mg II absorbers. The composite absorber spectrum is obtained by taking the geometric mean of 92 quasar spectra after aligning them in the restframe of 96 absorbers. By aligning the spectra according to absorber redshifts we reinforce the spectral features of the absorbers, and smooth over possible bumps and wiggles in the emission spectra as well as small features in the flat fielding of the spectra. The width of the observed absorption feature is 200-300 Å (FWHM), or  $0.4\text{-}0.6\ (\mu\text{m})^{-1}$  and the central wavelength is 2240 Å. These are somewhat different from the central wavelength of 2176 Å and FWHM=0.8-1.25  $(\mu\text{m})^{-1}$  found in the Galaxy. Simulations show that this discrepancy between the properties of the 2175 Å feature in Mg II absorbers and Galactic ISM can be mostly explained by the different methods used to measure them.

*Subject headings:* ISM: dust, galaxies: intergalactic medium, quasars: absorption lines

## 1. Introduction

The amount of dust at high redshift has implications both for the chemical evolution of galaxies and for observational strategies for detecting galaxies at high redshift. Quasar absorption systems offer an opportunity to study dust in these systems at a large range of redshifts and hence trace the chemical evolution. Quasar absorption systems also have the advantages of a simple geometry, being thin-screen absorbers backlit by quasars. Scattering or more complicated effects of mixed dust and stars do not therefore complicate the interpretation.

There are a few lines of evidence that indicate the presence of dust in quasar absorption systems. Fall, Pei & McMahon (1989) and Pei, Fall & Bechtold (1991) compare the spectral slope of quasars with and without damped Lyman- $\alpha$  absorbers and conclude that quasars

with damped Lyman- $\alpha$  absorbers are redder. From the analysis of 100 and  $60\mu\text{m}$  emission, Tanner et al. (1996) conclude that quasars with Mg II absorbers are redder in FIR emission than random quasars. Meyer & Roth (1990), Pettini & Bowen 1997, Pettini et al (1994, 1997) compare the observed gas phase abundance ratio of Cr (which depletes onto dust) and Zn (which does not) in quasar absorption line systems and conclude that a substantial fraction of the Cr must be in dust grains (cf Lu et al. (1996), Kulkarni, Fall & Truran (1997) for discussion on nucleosynthesis patterns of elements relevant to such a comparison).

Direct detection of spectroscopic features of dust would be more persuasive. Absorption features can be an easier way to study the ISM of high redshift galaxies than emission features: their strength is independent of the absorber's redshift, depending only on the column density (of dust or gas) and on the flux of the background source. The absorption bump at  $2175\text{ \AA}$  is the strongest spectral dust feature in the ultraviolet [UV] - optical wavelength range. The ratio of extinction at  $2175\text{ \AA}$  to  $A_V$  varies from  $A(2175)/A_V = 1.5\text{--}3.5$  (Cardelli, Clayton, & Mathis 1989), with the higher value prevailing for dust in the diffuse medium. McKee and Petrosian (1974) first pointed out that the absence of the  $2175\text{ \AA}$  feature would constrain the abundance of Galactic type dust in the high redshift damped Lyman- $\alpha$  systems. Since then there have been a few studies looking for the  $2175\text{ \AA}$  dust feature (Jura 1977; Smith, Jura & Margon 1979; Boissé & Bergeron 1988, Lanzetta, Wolfe & Turnshek 1989, Pei, Fall & Bechtold 1991). These studies constrain the  $2175\text{ \AA}$  feature to less than 1/10 the Galactic strength in a few damped Lyman- $\alpha$  systems. This feature is also seen at rest-wavelength of the quasar in PHL 938 and TON 490 (Baldwin 1977, Drew 1978)

The challenge in detecting the  $2175\text{ \AA}$  feature is that it is very broad,  $\text{FWHM} \simeq 350 \times (1+z)\text{ \AA}$ , and hard to distinguish from broad undulations in the quasar emission spectrum. Coadding a large number of quasar spectra after aligning them according to the absorber redshift randomizes spectral features due to quasars and small variations in the flat-fields, while reinforcing the features in the absorption systems. I apply this technique to 96 Mg II absorption systems from the survey by Steidel & Sargent (1992). The average redshift of the Mg II absorbers in this sample is  $z \simeq 1.2$ .

The main practical advantage of using the Mg II sample lies in the selection by the Mg II doublet at  $2800\text{ \AA}$ , close in wavelength to the  $2175\text{ \AA}$  absorption feature, so that a large fraction of the spectra from the survey had useful spectral coverage. Also, the Steidel & Sargent (1992) sample is a large, uniform survey with absorbers at a wide range of redshifts ( $0.2 < z < 2.2$ ). Most previous searches of the  $2175\text{ \AA}$  feature were carried out for damped Lyman- $\alpha$  systems, which have to be at  $z > 1.65$  to be observed from the ground. For high redshifts ( $z > 2$ ) the  $2175\text{ \AA}$  feature lies in the noisier red end of the spectra.

Also, one might expect high redshift absorbers in a young universe (at  $z \simeq 2$ ) to be less chemically evolved.

The presence or absence of the 2175 Å absorption feature can also help distinguish between the various extinction curves that have been observed in the Galaxy and the Large and Small Magellanic Clouds (LMC and SMC). The Far-UV extinction correlates with the properties of the 2175 feature; the broader the bump, the faster is the rise of FUV extinction (Fitzpatrick & Massa 1988). The presence of the 2175 Å feature correlates well with shallower far-UV rise of the extinction curve, implying less reddening (or difference in extinction) between Visible and far-UV bands. This is relevant for high redshift objects, which are particularly vulnerable to reddening/extinction because ground based optical observations correspond to rest-wavelength UV (Ostriker & Heisler 1984). The extinction and reddening in UV is not only high, but also highly variable, The extinction at 1250 Å may vary by 1.75 magnitudes between the bumpless SMC curve and the Milky Way curve.

In §2 I describe the analysis methods to extract the composite absorber spectrum. In §3 Monte-Carlo simulations are used to estimate the significance of the detection of 2175 Å feature in the composite spectrum. §4 includes a comparison of the feature seen in absorbers with that seen in the Galaxy and a discussion of dust-to-gas ratios and gas column densities implied by the measurement of the 2175Å feature.

## 2. Analysis

The composite absorber spectrum is derived from 92 quasar spectra from the Steidel & Sargent (1992, hereafter SS92) sample having 96 Mg II absorption systems. The red edge of the Lyman alpha forest absorption is bluer than the 2175 Å feature in all systems where the 2175 Å feature was in the observed wavelength range. Visual inspection showed that about 45 absorption systems were “clean” ; i.e. restwavelength  $2175 \pm 200\text{\AA}$  was in the spectral range and did not coincide with emission features of the quasar. The visual inspection was used only to estimate the number of absorbers contributing to the signal and not as a basis of rejecting or accepting spectra to be coadded.

First, the emission lines of the quasars are excised by removing data points within 6000 km/s of the following lines: Ly- $\alpha$  at 1215.7 Å C IV at 1549 Å C III at 1908.7 Å and Mg II at 2799.8 Å. Then the composite spectrum is derived by taking the geometric mean of the spectra in the SS92 sample after aligning them according to the redshift of the absorption systems. Because of such alignment any residuals in the spectrum which are correlated with quasars redshifts (e.g. Fe II emission) are randomized if the emission

and absorption redshifts are not correlated. The intrinsic quasar spectra are multiplied by  $(1 + Z_{qso})/(1 + Z_{abs})$  to shift them to the absorber restframe. The distribution of  $(1 + Z_{qso})/(1 + Z_{abs})$  is fairly featureless and decreases monotonically from 1 to 2.

If  $f_\lambda$  is the intrinsic quasar spectrum and  $\tau_i(\lambda)$  is the dust absorption in the  $i$ th Mg II system, the geometric mean gives directly the average opacity due to dust.

$$(\prod f_\lambda e^{-\tau_i(\lambda)})^{1/n} = (\prod f_\lambda)^{1/n} \times e^{-\sum \tau_i(\lambda)/n}$$

In practice, the geometric mean was calculated by running a boxcar mean on  $\log(f_\lambda)$ . Figure 1 shows the composite spectrum using box-car of width 5 Å. Different boxcar filters were used and the final result was relatively insensitive to the width of the filter for widths  $< 20$  Å.

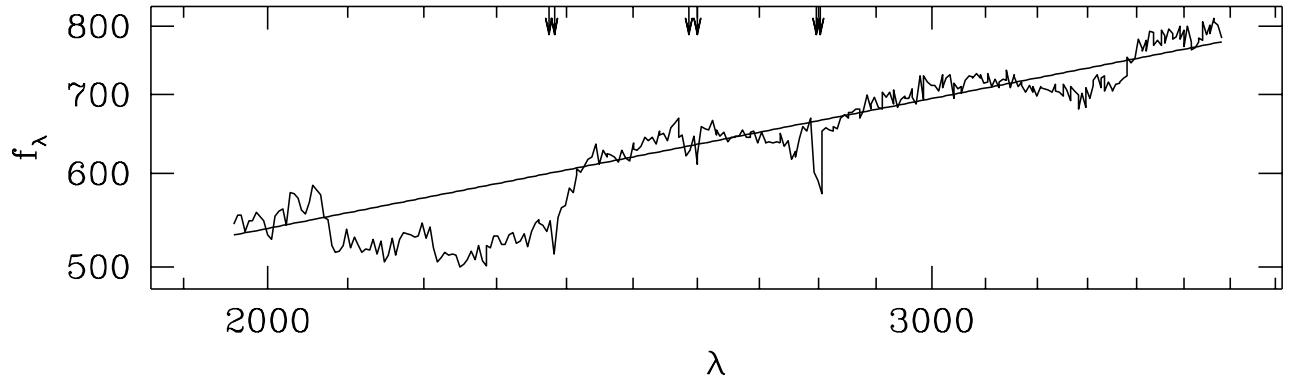


Fig. 1.— The composite spectrum of quasar absorbers shown here is obtained by removing quasar emission lines, aligning the spectra according to the absorber redshift, and taking the geometric mean of the spectra. The geometric mean is calculated using a boxcar mean of width 5 Å on  $\log(f_\lambda)$ . The straight line is the power-law fit to the spectrum at  $\lambda > 2500$  Å. The most prominent feature in this spectrum is the absorption feature centered at 2240 Å which we identify to be the 2175 Å dust feature seen in the Galaxy. Other metal lines are also seen: the Mg II doublet at 2800 Å and the Fe II lines at 2600, 2586.65, 2382.77, and 2374.46 Å.

### 3. Error Analysis

The absorption band seen at 2240 Å is significant if only the random noise is considered. In this section I will attempt to get a more realistic estimate of the significance of this

detection and to test whether any systematic effects can spuriously produce this feature. I test for the systematics in two different ways described below.

### 3.1. Randomizing the absorber redshifts

To test how likely it was to get this feature spuriously, I repeated the procedure of making the composite spectra, after randomly shuffling absorber redshifts with respect to the spectra. The amplitude of the composite spectra thus produced at  $2240 \text{ \AA}$  was measured in 100 simulations. Only one simulation had a negative deviation equal or exceeding the observed in the real spectrum. The variance of the deviation at  $2240 \text{ \AA}$  in these random samples was found to be 0.019. This implies that the dust feature in Figure 1 is significant at  $2.7\sigma$  level at peak (but there are about 40 points in the absorption feature at  $> 2\sigma$  level, so the total significance of the detection is higher). Figure 2 shows the mean and standard deviation of composite spectra in 100 such simulations.

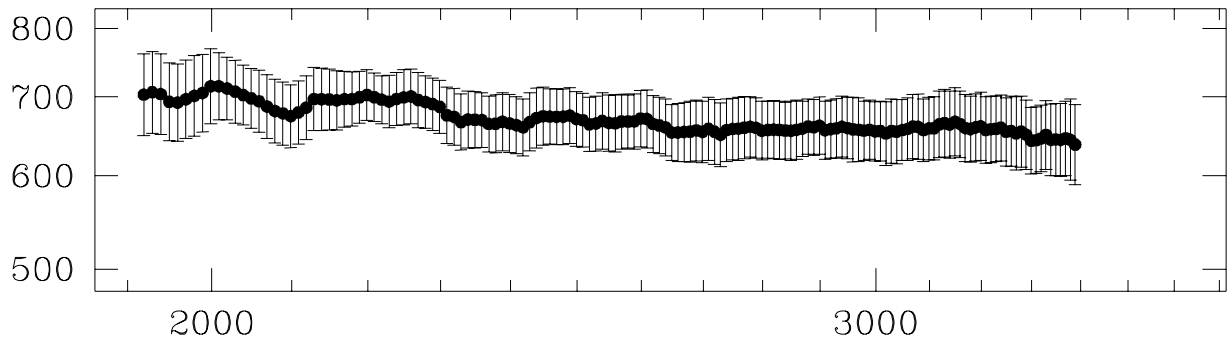


Fig. 2.— This is the resultant spectrum if we randomly mix the absorber redshifts in the sample of SS92, and form a composite spectrum in the same manner as in Figure 1. We see no features comparable to the  $2240\text{\AA}$  dip in Figure 1. From the noise estimated from 100 such composite spectra with randomized redshifts we conclude that the peak deviation of the  $2240\text{\AA}$  dip in Figure 1 is  $2.7\sigma$  significant.

### 3.2. Using a composite quasar emission spectrum

It is possible that the absorption feature could be caused by small-amplitude broad emission features in the quasar spectrum (e.g. FeII emission near  $2400 \text{ \AA}$ ) combined

according to the  $Z_{qso}, Z_{abs}$  set in the SS92 sample used. To check that possibility I used a composite quasar spectrum without absorption features to replace the real spectra in the SS92 sample. This spectrum was obtained by Zheng et al. (1997) by combining low redshift quasar spectra observed with HST after removing the few foreground absorbers in those spectra. Shifting and combining many copies of the Zheng et al. spectrum using the same treatment applied to the SS92 sample yields a featureless continuum (Figure 3).

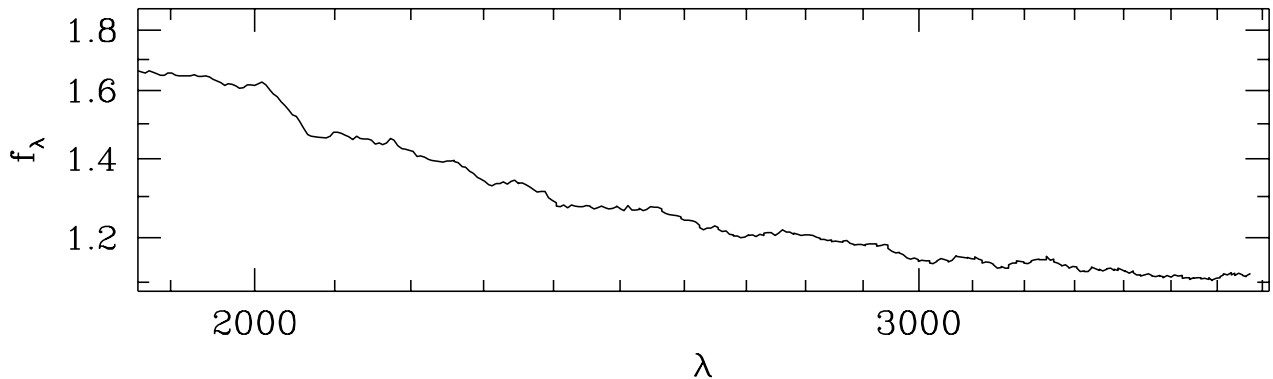


Fig. 3.— The composite spectrum derived in the same manner as Figure 1, except the real spectra from SS92 have been replaced by a low-redshift, high S/N quasar composite spectrum from Zheng et al. 1997 which lacks absorption lines. The spectra are appropriately redshifted to the absorber redshifts taken from SS92. We see no feature comparable to the 2240 Å absorption in Figure 1.

#### 4. Results and Discussion

The most prominent feature in the composite spectrum obtained in Figure 1 is the broad absorption bump with a central wavelength of 2240 Å (or  $4.46\mu\text{m}^{-1}$ ) and FWHM of 200-300 Å (or  $0.4 - 0.6\mu\text{m}^{-1}$ ). The peak amplitude of the absorbing feature is 10% (Figure 1). Other narrow lines observed in the composite spectrum of the absorbers are Mg doublet at 2796 & 2803 Å and Fe II lines at 2600, 2586.65, 2382.77 and 2374.46 Å.

The interpretation of this absorption feature as the interstellar dust feature seen at 2175 Å in our Galaxy depends on whether it lies within the range of observed extinction curves or theoretical models for dust. Both are somewhat uncertain. The carrier of this feature is most probably graphite or amorphous carbon (Stecher & Donn 1965, Gilra 1971, see review by Draine (1989)). In the Milky Way this feature is observed to have a fairly

constant central wavelength ( $\lambda_0 = 2176 \pm 9 \text{ \AA}$ ) (Fitzpatrick & Massa 1986), while the width of the feature varies from  $0.77 \mu\text{m}^{-1}$  to  $1.25 \mu\text{m}^{-1}$ . Diffuse regions show narrower features, as do regions with higher levels of radiation. This is consistent with the observed feature in Mg II absorbers being narrow, as Mg II absorption comes from regions of relatively low column density of neutral hydrogen. Although the central wavelength of the feature associated with Mg II systems is high for interstellar dust, circumstellar dust in Hydrogen poor environments shows an absorption bump at  $\lambda_0 = 2400 \text{ \AA}$  (e.g. Greenstein 1981, Hecht et al. 1984, Drilling et al. 1997). The dust models have no difficulty reproducing an absorption bump with  $\lambda_0 = 2240$ ; such a feature can be produced by including more large grains (Draine & Malhotra 1993) or amorphous carbon grains which produce an absorption bump at  $2400 \text{ \AA}$ .

To estimate the effect of the above methods of extraction on the properties of the feature I perform Monte Carlo simulations in which a dust absorption feature with known properties is artificially added to spectra whose absorber redshifts are shuffled (as in §3.1). Applying Galactic extinction curve with  $A_V = 0.3$ , and with the  $2175 \text{ \AA}$  feature at central wavelength of  $\lambda_0 = 2175 \text{ \AA}$ ,  $\text{FWHM} = 0.8 \mu\text{m}^{-1}$  and, I recover an absorption feature with absorption amplitude 20%,  $\text{FWHM} = 0.5 \mu\text{m}^{-1}$  and  $\lambda_0 = 2230 \text{ \AA}$  (Figure 4). This experiment shows that the procedure used to derive the coadded absorption spectrum underestimates the width of the feature. This may be because the feature is very wide compared to the wavelength coverage (the FWHM of the feature  $\sim 1/2$  the wavelength coverage). The overestimate of the central wavelength of the feature is presumably due to limited spectral coverage blueward of the feature. The  $2175 \text{ \AA}$  feature in Galaxy, LMC and SMC is determined by comparing the spectra of reddened and unreddened stars of the same spectral type and does not suffer from these biases.

Because of the abundance variations and saturation of the Mg II lines at  $2800 \text{ \AA}$ , we cannot estimate the column density of hydrogen and the gas-to-dust ratio in these systems. A peak amplitude of 10% in this feature implies  $A_V = 0.15$  using the Galactic extinction law (Cardelli, Clayton, & Mathis 1989). Using the local gas-to-dust ratio in the galaxy (Bohlin et al. 1978) -  $N(\text{H})/A_V = 2 \times 10^{21} \text{ cm}^2$ , we derive an average  $N(\text{H}) = 3 \times 10^{20}$  for these systems. Models show that Mg II absorption systems are associated with Lyman limit systems, i.e.  $N(\text{HI}) > 10^{17.2}$  (SS92). The column density distribution of Lyman limit systems is  $N(\text{HI}) = BN^{-\beta}$ , with  $\beta = 1.2 - 1.7$  (Steidel, Sargent & Boksenberg 1988, Lanzetta 1991). Averaging over this distribution between column densities  $21.8 > \log(N(\text{HI})) > 17.2$ , yields an average column density  $N(\text{HI}) \simeq 10^{19}$ . A lower limit to the average column density can also be derived from the fraction of damped Ly- $\alpha$  systems ( $N(\text{HI}) > 2 \times 10^{20}$ ) among Mg II systems. This fraction is estimated to be  $0.13_{-0.04}^{+0.29}$  for  $z \simeq 2$  systems and  $\leq 0.14$  for  $z \simeq 0.8$  systems (Rao, Turnshek

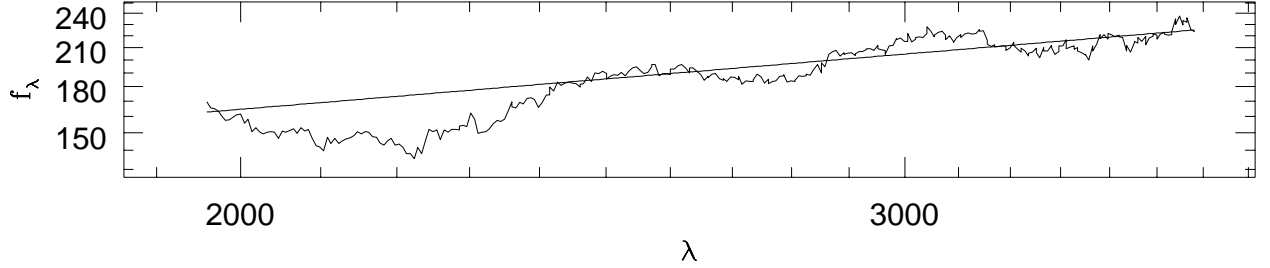


Fig. 4.— This spectrum is derived by shuffling the quasars with respect to the absorber redshifts so that the real absorption features disappear, and then putting an artificial 2175 Å feature into each spectrum at the shuffled redshifts and coadding in the manner described in section 2. This procedure enables a comparison of input parameters of the absorption bump with the parameters derived by subtracting a linear baseline and coadding several spectra. The FWHM is underestimated, input  $\text{FWHM} = 0.8 \mu\text{m}^{-1}$  yields a  $\text{FWHM} = 0.5 \mu\text{m}^{-1}$  in the final spectrum.

& Briggs 1995). The damped systems alone would imply an average column density of  $N(\text{HI}) \gtrsim 3 \times 10^{19}$ . The column density of neutral gas should also be corrected for ionized gas column density. The ratios of ionized to neutral column density expected from photoionization model  $N(\text{HII})/N(\text{HI}) \lesssim 30$  for Lyman limit systems and  $N(\text{HII}) \simeq N(\text{HI})$  for  $N(\text{HI}) \simeq 10^{19}$  (e.g. Bergeron et al. 1994); this may increase the average  $N(\text{H})$  of the Mg II systems. Molecular gas has been found in a few absorption systems (Ge & Bechtold 1997, Walker, Bechtold, Black 1994). The strength of the 2175 Å feature observed is roughly consistent with Galactic type dust and dust-to-gas ratio. Given the marginal detection of this feature and the uncertainty in the column density of Hydrogen it is difficult to draw any firm inference about the dust-to-gas ratio and the nature of the extinction curve for these systems.

Deep imaging of Mg II absorption systems has revealed them to be normal star forming galaxies (Bergeron, Cristiani & Shaver 1992, Steidel et al. 1994, Elston et al. 1991). It is not yet clear whether the Mg II systems arise from disks or halos of galaxies or from material torn from galaxies in interactions (Churchill et al. 1997, Bowen et al. 1996). If the damped Lyman- $\alpha$  systems are similar to the Mg II systems, a similar analysis should allow for an easier detection of the 2175 Å feature since the gas column densities are higher. Possible detections of the 2175 Å feature at quasar redshifts have been reported (Baldwin

1977, Drew 1978), but attempts to detect this feature in individual absorbers have failed (Jura 1977, Smith, Jura & Margon 1979; Boissé & Bergeron 1988, Lanzetta, Wolfe & Turnshek 1989, Pei, Fall & Bechtold 1991), possibly because (a) it has been looked for in high redshift damped Lyman- $\alpha$  systems, which may be less evolved chemically and (b) It is difficult to determine the intrinsic quasar continuum shape accurately enough to detect an extinction feature of typical FWHM  $\simeq 700\text{\AA}$  in observer rest frame. To be able to do that one may need to coadd many quasar spectra as described in this paper.

## 5. Summary and Conclusions

We have evidence for the  $2175\text{\AA}$  dust feature in quasar absorption systems identified by the Mg II doublet at  $2800\text{\AA}$ . This feature implies the presence of dust quite similar to Galactic dust. So far this feature had been observed only in the local galaxies (Milky Way, LMC, SMC, M31, M101) where individual stars can be resolved and their spectra compared to detect dust absorption features in reddened vs unreddened stars of the same type. In this study I have used the method of coadding many (96) spectra in the absorber restframe to detect the wide (FWHM  $\simeq 350\text{\AA}$ ) dust absorption feature. Most of the difference in properties of the bump (e.g. FWHM) derived in quasar absorption systems and Galactic dust is shown to be due to different methods used to derive these measurements.

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